(54) Epitaxy for growing compound semiconductors and an InP substrate for epitaxial growth

(57) Hillocks arise on the films, when compound semiconductor films are grown on an InP wafer having a surface near a (100) orientation. Off-angle wafers have been adopted for a substrate in order to suppress the occurrence of hillocks. The off-angle Θ from a (100) plane is not a sole factor for ruling the generation of hillocks. There is a concealed parameter which determines the generation of hillocks. What induces hillocks on the growing film is the defects on the substrate itself. No hillocks originate on a part of an InP wafer without dislocations. The role of the off-angle Θ of the substrate is preventing the influence of the dislocations from transmitting to the films. A smaller density D of the defects on the substrate allows a smaller off-angle Θ for suppressing the hillocks from arising. A bigger density D of the defects demands a larger off-angle for the substrate so as to forbid the hillocks from originating. An inequality $\Theta \geqq 1 \times 10^{-3} D^{1/2}$ is the condition for annihilating hillocks. More precise condition is $\Theta \geqq 1.26 \times 10^{-3} D^{1/2}$.

FIG.5

D : dislocation density
Θ : off-angle from (100)
a : height of edge
(spacing of terraces)
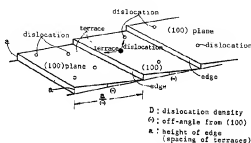
Description

This invention relates to an epitaxial method for suppressing the occurrence of hillocks which are likely to appear on a thin film of a compound semiconductor epitaxially grown on a compound semiconductor substrate in vapor phase. The compound semiconductor substrate means a GaAs substrate, an InP substrate and so forth. Vapor phase epitaxy is an influential method of growing a compound semiconductor film of either the same component as the substrate or the components different from the substrate material. The vapor phase epitaxy includes MOCVD (Metal-Organic Chemical Vapor Deposition), MBE (Molecular Beam Epitaxy), Chloride CVD or Halide CVD. This invention is capable of being applied to all of the vapor phase epitaxy methods.

This invention claims a priority based on Japanese patent application No.6-240680 (240680/'94) filed on September 8, 1994.

Conventional vapor phase epitaxy, in particular, OMVPE (or MOCVD) suffers from the problem that convex defects which are called hillocks appear on surfaces of epitaxially grown films. A lot of investigations have been done for clarifying the relations between the generation of the defects and each factor, that is the surface orientation of substrates, the speed of crystal growth and the temperature of the growth in order to reduce the number of the hillocks.

For example, Japanese Patent Laying Open No.2-239188 (239188/'90) paid attention to the problem of surface defects called "growth pyramid" or "faceted defects" which arose in the vapor phase epitaxy of compound semiconductors. This prior application described that the "off-angle" method had been adopted to suppress the occurrence of the surface defects. The off-angle method is a method of growing films epitaxially on a wafer which has an orientation of the surface inclining at 1° to 7° to a (100) plane. Off-angled wafers, however, cannot be adopted for making special devices, for example, laser diodes which require forming gratings on the surface waveguides. The grating having regularly spaced grooves demands a just-(100) wafer as a substrate. The just-(100) wafer means here a wafer having a surface which correctly corresponds to a (100) plane. An off-angled (100) wafer indicates a wafer having a surface which inclines slightly to a (100) plane. If the inclination angle is α, the wafer is designated as a (100)± α. The application mentioned that some of the off-angle wafers were still accompanied by the faceted defects and a lot of faceted defects arose in a small off-angled wafer having an off-angle less than 0.1 degree. Thus Japanese Patent Laying Open No.2-239188 proposed an improvement of vapor phase epitaxy including the processes of preparing an off-angle wafer with a slanting-angle between 0.1° and 0.5° to a (100) plane, maintaining the substrate wafer at a temperature between 600°C and 700°C, and growing semiconductor films on the heated, off-angled substrate in vapor phase.

Japanese Patent Laying Open No.5-301795 (301795/'93) proposed a method of reducing droplet-defects appearing on the surface of a substrate in an epitaxial growth of compound semiconductors in vapor phase. For decreasing the number of the droplet-defects, the prior art suggested an inequality

$$0.011V^{1.5} + 6.21 \times 10^{20} T^{-7.5} \le \theta \le 0.20$$

where θ is the off angle of the wafer from a (100) plane, V is the speed of the epitaxial growth and T is the temperature of the substrate. The application mentioned that the defects could be decreased by growing the compound semiconductor films on the wafers which satisfied the inequality. Faster growth demands a higher substrate temperature. Lower growing speed requires a reduction of the substrate temperature to the contrary. This is the meaning of the inequality. It is, however, still unclear why the speed V and temperature T are accompanied with the order of magnitude of 1.5 and -7.5 respectively.

Japanese Patent Laying Open No.64-32686 (32686/'89) produced avalanche photodiodes by the halogen transport CVD method. The application discussed the problems of both an occurrence of a lot of hillocks and a big fluctuation of film thickness of the avalanche layer, when InP wafers having a wafer which satisfied ±0.1° from a (100) plane were adopted as substrates. Then this prior art suggested an epitaxial growth having an off-angle InP wafers inclining at 0.2 degree to 0.5 degree to a (100) plane, and forming epitaxially a light absorption layer and an avalanche layer of the off-angle substrate wafer. They said that the occurrence of hillocks was suppressed by the off-angle substrate.

Japanese Patent Laying Open No.64-22072 (22072/'89) pointed out the problems of the dispersion of the thicknesses of a window layer and a buffer layer, and of the fluctuation of the depth of pn-junctions, when InP type photodiodes were produced on just-(100) InP wafers by the halogen transport vapor phase epitaxy. The prior art suggested a use of an off-angled InP with an off-angle between 0.2 and 0.5 on which a buffer layer and a light absorption layer were deposited. They mentioned that the contrivance succeeded in reducing the fluctuation of the film thicknesses and in enhancing the yield of the products.

Japanese Patent Laying Open No.64-15914 described the problem of the difficulty of controlling the film thickness due to the occurrence of hillocks, when InP photodiodes were produced by growing epitaxially InGaAsP films and so forth on a just-(100) InP wafer by halogen transport CVD method. They reported that the uniformity of the film thickness was improved by growing multi-layered InGaAsP thin films on an off-angle InP wafer inclining at an angle between 0.2 degree and 0.5 degree to a (100) plane.

Japanese Patent Laying Open No.1-270599 (270599/'89) alluded the problems of the weak photoluminescence (PL) of a double-hetero structure produced

on a just-(100) InP wafer by an MBE method and of the high threshold current of the laser diodes further made on the same double-hetero structure. For avoiding these difficulties, the application suggested a method ot fabricating the double-hetero structure by the MBE method on an off-angle InP water having a surface slanting at 0.5 degree to 2 degrees to a (111) plane. This prior art used a (111) wafer instead of a (100) wafer. This report mentioned that the threshold current was reduced by the adoption of the off-angle (111) InP wafer.

Japanese Patent Publication No.4-73610 (73610/92) proposed an epitaxial growth of compound semiconductor films on an off-angle GaAs wafer slanting at 0.1 degree to 1 degree to a (111)B plane for making quantum-well laser diodes or high speed FETs based on the two-dimensional electron gas. The inventors told that the inclination of a GaAs water ranging trom 0 1 degree to 1 degree made the epitaxial films mirror-smooth and enhanced the photoluminescence. They judged the off-angle (111) GaAs wafer was superior to the (001) GaAs wafer.

Japanese Patent Laying Open No.62-88318 (88318/87) proposed an epitaxial growth of thin compound semiconductor films on an off-angle (111) GaAs wafer slanting at an angle between 0.1° and 1° to a (111) B plane. They alleged that the thin films deposited on the off-angle (111)B GaAs wafer exhibited stronger photoluminescence than the thin film made on a (001) GaAs wafer.

Japanese Patent Laying Open No.3-16993 (16993/91) pointed out the problem of the ruggedness of thin films epitaxially grown on a just-(100) GaAs water in vapor phase. The ruggedness was induced by the striped morphology called "cross-hatching". They said that the cross-hatchings were reduced by adopting an off-angle wafer slanting at an angle between 0.5 degree and 10 degrees to a (100) plane.

Japanese Patent Laying Open No.2-288223 (288223/90) pointed out the problem of the occurrence of rice-grain defects appearing on surfaces of HEMTs (High Electron Mobility Transistor) which were made by growing AlGaAs films on (100) GaAs wafers. They said the rice-grain defects were caused by the inclination of the (100) GaAs wafer to a (100) plane. They alleged that the deviation of the orientation of the (100) wafer should be less than 0.15 degree, preferably less than 0.05 degree in order to prevent the rice-grain defects from arising on the surfaces. This opinion contradicts to the prior art which have been explained till now.

Japanese Patent Laying Open No.1-128423 (128423/89) disclosed the employment of an off-angled GaAs wafer slanting at an angle of 0.5 degree to 10 degrees to a (100) plane in order to avoid the ruggedness of the film surface brought about by growing a thin films including aluminum on a GaAs wafer either by an MBE method or an MO-MBE method.

Almost all of the prior art adopted off-angle InP wafers slanting at a small angle to a (100) plane as a sub-

strate of the epitaxial growth of compound semiconductor films for preventing the surface of the grown films from being rugged. Different reporters recommended different scopes of the slanting angle of an InP wafer to a (100) plane. All of them inclined the surfaces of InP wafers to a principal plane (100) for suppressing the ruggedness appearing on the film surfaces.

All of the prior art took account only of the inclination of the film surface to the principal plane (100). No attention, however, has been paid to the memory of the substrate left in films , that is, the relation between the substrate and the films. They deemed that the off-angle substrate had the role of inclining the orientation of the films to the principal plane. They thought the purpose of using an off-angle wafer is to make the film surface smooth. Furthermore, these prior art taught us nothing of the relation between the property of the substrate and the occurrence of hillocks.

By contrast, the inventors of the present invention were aware of a big difference of the density of hillocks appearing on the different films which have been grown on the substrates having the same off-angle. Some films indicate a low density of hillocks but other films exhibit a high density of hillocks, even if the films were deposited on the substrate wafers having the same off-angle. Almost all of the prior art mentioned till now defined optimum ranges of the off-angles Θ from a (100) plane, and explained the density of hillocks would be reduced as a function of the off-angle Θ of the substrate wafers. Thus they asserted the ruggedness of the epitaxial wafer should be decreased uniformly in accordance with an increase of the off-angle Θ.

The present inventors, however, dissent from the prevalent opinion. Even the substrates having the same off-angle deviating from the same principal plane make epitaxial films showing very different states of hillocks. The inclination angle of the substrate from the principal plane is not a unique parameter which exclusively rules the occurrence of hillocks. Otherwise, hillocks appear or do not appear by some reason other than the off-angle of the substrate or the films. The appearance of hillocks is contingent on a certain tact other than the inclination of the film surface to the principal plane. Some substrate with a small off-angle (inclination angle) has a small density of hillocks in the films grown on the substrate. Other substrate with a big off-angle has a big density of hillocks in the films deposited on the substrate. What does cause such a reverse relation between the off-angle and the hillock density? There should be a hidden parameter of determining the occurrence of hillocks.

One purpose of the present invention is to clarify the reason why the hillocks are induced on the compound semiconductor films grown on an InP substrate. Another purpose of the present invention is to provide an vapor phase epitaxy of compound semiconductor in which the off-angle is pertinently determined for suppressing the generation of hillocks. A further purpose of the present invention is to provide an epitaxial InP wafer without hill-

ocks. A still further purpose of the present invention is to provide an InP wafer which is immune from hillocks when epitaxial films are grown on it.

This invention pays attention to the defects on the substrate itself. The Inventors have discovered that the density of the hillocks of the film is contingent on the defect density of the substrate itself. The hidden parameter which determines the occurrence of the hillocks turns out to be the density of the inherent defects on the substrate. Further two elements which determine the density of the hillocks on the film are the inclination angle of the substrate and the density of the inherent defects of the substrate. The Inventors have discovered the fact for the first time.

Then this invention changes the inclination angle (off-angle) of the substrate as a function of the density of the defects on the substrate for preventing hillocks from originating on the film grown on the substrate. When the substrate has a lower density of the defects, a smaller off-angle of the substrate is allowable. On the contrary, when the density of the defects is higher, a wafer of a bigger off-angle shall be chosen for the substrate. Then the minimum off-angle of a wafer can be determined as a function of the defect density on the substrate for hindering hillocks from arising.

What is the function which determines the compensatory relation between the inclination angle and the defect density?

The Inventors have found the following properties controlling the epitaxy of an InP film on an InP substrate wafer.

①When the average EPD (Etch Pit Density) is 25000 cm^{-2} on an InP wafer, no hillock appears on the InP wafer having an off-angle larger than 0.2° .

②When the average EPD is 3000 cm^{-2} on an InP wafer. no hillocks arise on the InP wafer having an off-angle bigger than 0.07° .

③When the average EPD is 1000 cm^{-2} on an InP wafer. no hillocks originate on the InP wafer having an off-angle bigger than 0.04° .

Therefore, the minimum inclination angle Θ is contingent upon the density of defects (EPD) on the substrate. The Inventors have deduced a relation ruling the occurrence of hillocks from the experiments①②and③. The relation is simply expressed by an inequality

$$\Theta \geqq 1.26 \times 10^{-3} D^{\frac{1}{2}},$$

where Θ is an allowable off-angle denoted by the unit of degree (not by the unit of radian), and D is the defect density (EPD) in the unit of cm^{-2} on the wafer. This is a fundamental inequality on which this invention relies.

The defects (dislocations) sometimes disperse irregularly on a wafer and a microscopic defect density D varies locally on the wafer. In such a random distribution

of defects, the expression of the parameters D and Θ with three digits may be less significant. In this case, by taking into account only the uppermost effective number, the inequality is reduced to

$$\Theta \geqq 1 \times 10^{-3} D^{\frac{1}{2}}.$$

The Inventors have noticed the relation between the defects of the substrate and the occurrence of the hillocks for the first time. Namely, the bigger the density of the defects is, the higher the probability of the occurrence of the hillocks is. The fewer defects the substrate has, the lower the frequency of the occurrence of the hillocks rises. When wafers are made by slicing a single crystal ingot, the off-angle Θ of the wafers from (100) plane is first determined and the ingot is cut into wafers in parallel with a plane with the determined off-angle. According to this invention, the minimum inclination angle Θ_{min} depends on the defect density of the substrate. The dependence is clearly described by the inequality $\Theta \geqq 1 26 \times 10^{-3} D^{\frac{1}{2}}$ (more roughly $\Theta \geqq 1 \times 10^{-3} D^{\frac{1}{2}}$).

A small density of defects on the substrate allows a small inclination angle Θ for preventing the hillocks from originating. The suppression of the hillocks requires a large inclination angle Θ for the wafers with lots of defects. The optimum off-angle Θ depends on the defect density on the wafers from the standpoint of eliminating the hillocks.

There is, however, a problem. An ingot is sliced into a plurality of as-cut wafers. The as-cut wafers are etched and polished into mirror-wafers with mirror-smooth surfaces. The defects are counted by etching the mirror-wafers with a special etchant enabling dislocations to appear on the surfaces. The defect density cannot be reckoned before being cut into wafers. Thus slicing an ingot precedes counting defects.

An approximate density of defects, however, can be measured by cutting a part of an ingot, obtaining a small sample wafer, etching the sample, and counting the dislocations appearing on the sample wafer after etching. The inclination angle can be determined by the approximate defect density calculated from the sample wafer. Then the ingot can be sliced at the off-angle determined by the defect density measured for the sample wafer. Off course, the defect density fluctuates in the axial direction in the ingot and the defect density of each wafer will be different from the density of the sample wafer. The average density of defects can be surmised by the value of the sample wafer.

Effects of the present invention are now explained. It has been known that the surface of a film becomes rough, if a compound semiconductor film is epitaxially grown on a just (100) InP wafer. It has also been known that the adoption of a small-angle InP wafer alleviates the roughness of the surface of the film. Semiconductor lasers have sometimes been fabricated on a slightly off-angle InP wafer inclining to a (100) plane. Nobody, however, has been aware of the influence of the dislocations on the InP substrate upon the films grown on the

substrate.

This invention points out a strong correlation between the defects (dislocations) on the substrate and the generation of the hillocks for the first time. The defects on the substrate have been deemed to have no relation to the hillocks on the film. The inclination angle (off-angle) can be small enough for suppressing the hillocks, if the substrate has a small density of defects. On the contrary, the wafer with a large density of defects requires a large off-angle for the substrate in order to annihilate the hillocks.

This invention proposes a clear criterion for the off-angle Θ as a function of the defect density D to make a smooth film on an InP wafer. This invention enables an operator to design a correct off-angle in slicing an InP single crystal ingot into a plurality of as-cut wafers. The operator can slice an InP ingot into wafers which are immune from the origination of hillocks by the processes of cutting a small part of the ingot, obtaining a sample wafer, etching the sample wafer by some etchant, measuring the EPD on the sample wafer, determining an optimum off-angle, cutting the ingot at the determined off-angle. The fabrication of devices, i.e. laser diodes, requires the wafers which have an orientation with the least deviation from a (100) plane. Thus the operator will be able to cut the ingot at the best angle which is the smallest off-angle in the solutions of the inequality.

The invention will be more fully understood from the following description given by way of example only with reference to the several figures of the accompanying drawings in which,

Fig. 1 is a graph showing the relation between the off-angle Θ of an InP substrate and the density of hillocks appearing on the film with a parameter of the defect density of the substrate, when an assembly of films InP/InGaAs/InP is grown epitaxially on the InP substrate.

Fig.2 is a Nomarski microscope photograph on the uppermost InP film epitaxially grown on the InP substrate in the same experiment as in Fig.I.

Fig.3 is a Nomarski microscope photograph of the Hüber-etched substrate revealed by eliminating the films which were grown on the substrate.

Fig.4 is a schematic view of the band structure showing the energy state on an atom in a trap level.

Fig.5 is a perspective view of terraces for explaining the behavior of an atom whether the atom goes into a trap or to the step of the terrace, when an atom falls on the terrace.

To achieve the foregoing objects and in accordance with the purpose of the invention, embodiments will be broadly descried herein.;

A set of thin films InP/InGaAs/InP was epitaxially grown on single crystal InP wafers which incline at a certain off-angle Θ to a (100) plane by the OMVPE (Organometallic Vapor Phase Epitaxy) method. The inclination angles of the wafers range from 0° to 0.2° .

In the growth of the films, the substrate was heated at 873K. The speed of the growth was 1.0μm/hr. Then

the epitaxial wafers were cooled and investigated. The number of the hillocks appearing on the uppermost InP film was counted by the observation through a microscope. Then the relation between the hillocks on the film and the defects on the substrate was examined. The wafers were classified into three degrees of defects. First kind of wafers has an average defect density (EPD) of 25000 cm⁻². Second kind of wafers has a smaller average defect density of 3000 cm⁻². Third kind of wafers has a far smaller average defect density of 1000 cm⁻²

Fig. 1 shows the relations between the off-angle of the wafers to a (100) plane and the hillock density on the top film with a parameter of the average defect density on the substrate. Blank triangles denote the results on the substrate having an average EPD of 1000 cm⁻². Blank rounds indicate the results on the substrate of an average EPD of 3000 cm⁻². Blank squares show the results on the substrate of the average EPD of 25000 cm⁻².

The wafer of the average EPD of 1000 cm⁻² has a hillock density of 1000 cm⁻² on the film when the off-angle is zero, i.e., Θ = 0. An increase of the inclination angle Θ decreases the hillock density drastically. About Θ = 0.03° reduces the hillock density down to 100 cm⁻². Despite the fluctuation, the hillock density falls to zero at the inclination angle Θ = 0.04° . No hillock appears on the InP wafer of an off-angle more than 0.04° , if the InP wafer has an EPD less than 1000 cm⁻².

The InP wafer of the average EPD of 3000 cm⁻² has a hillock density of 3000 cm⁻² on the film when the off-angle is zero. i.e., Θ = 0. A rise of the inclination angle reduces the hillock density. Θ = 0.04° brings about a low hillock density of about 1000 cm⁻²

The wafer of the average EPD of 25000 cm⁻² has a hillock density of 25000 cm⁻² when the off-angle is zero, i.e., Θ = 0. Even at Θ = 0.04° , the hillock density on the film is still 25000 cm⁻². Θ = 0.07° decreases the hillock density down to about 1000 cm⁻². At Θ = 0.20° , the hillock density on the film reduces to zero.

These experiments have been done on the condition that the growing rate is 1.0μm/hr and the substrate temperature is T= 873K (600°C). This Inventors, however, have confirmed that the same correlation rules over the inclination angle and the hillock generation on InP wafers at a temperature between 450°C and 800°C at a growth rate between 0.05μm/hr and 20μm/hr.

The relation between the hillock generation and the defects on the substrate which the Inventors have found is valid in general for wide ranges of temperature and growing speed.

An astonishing fact was found out with respect to the correlation between the defects on the substrate and the hillock generation of the film. Fig.2 is a Nomarski microscope photograph of the top film of a set of films InP/InGaAs/InP epitaxially grown on a Fe-doped just (100) InP wafer by the OMVPE (Organometallic Vapor Phase Epitaxy). Thus the epitaxial wafer has a multilayered structure of InP/InGaAs/InP/InP(substrate). The layers are denoted at the upper right of Fig.2. The magnification is

approximately 100. The arrow shows the object surface of the observation. Elliptical defects appear on the top InP film. These defects are called hillocks.

Then the InP/InGaAs/InP films were eliminated from the InP substrate. The surface of the substrate emerged. The surface of the substrate was Huber-etched. Fig.3 is a Nomarski microscope photograph of the Huber-etched surface of the substrate with a magnification of approximately 100. The arrow shows the object surface of the observation.

A comparison reveals a surprising fact that the positions of the hillocks in Fig.2 correspond one to one to the positions of the defects in Fig.3. This result indicates that a hillock grows just on a dislocation of the substrate with a zero off-angle Θ = 0. Such a dislocation on the substrate triggers a hillock on a film grown on the substrate. The film transcribes the defects on the substrate with hillocks for just (100) wafers. In the case of Θ = 0, hillocks arose all on the dislocations of the substrate. The hillocks correspond one to one to the dislocations for non off-angle wafers. Hillocks are transcriptions of dislocations.

Fig.1 indicates that the density of hillocks is equal to the density of dislocations (EPD) for all cases at the extremity of Θ = 0. The result is attributable to the rigorous correspondence between the hillocks and the dislocations. A hillock is generated by transcribing a dislocation on a just (100) wafer.

However, if the orientation of the substrate deviates from a (100) plane, all the dislocations on the substrate are not transcribed on the film as hillocks. The deviation of the substrate orientation, namely the off-angle seems to have a tendency of erasing the memory of the defects on the substrate. The off-angle is negative to the full copy from the dislocations to hillocks. If the substrate has a small density of the dislocations, a small inclination angle is sufficient to erase the memory of the dislocations and to make a smooth film without hillocks. On the contrary, a substrate with a big dislocation density requires a big off-angle so as to erase the memory of the defects of the substrate. The necessary off-angle is contingent on the inherent dislocation density of the substrate.

In any case, the defects on the substrate generate the hillocks on the film. Few hillocks occur on the region without defects. The inclination angle of the substrate from a (100) plane conceals some of the dislocations on the substrate. What prevents the film from transcribing the defects is the inclination angle (off-angle) Θ. The experiments revealed the phenomenal correlation between the defects and the hillocks and gave an effective means for suppressing the occurrence of hillocks.

Why do the hillocks relate to the inclination angle Θ and the defect density? What does rule the correlation among the inclination angle Θ, the defects and the hillocks? This invention is not still self-consistent unless the reason is clarified.

The following is the reason that the Inventors surmised. A film is grown on a substrate by the OMVPE

method. The atoms which arrive at a spot on the surface of the substrate are either captured at the same place into the lattice structure or displaced to another spot of lower potential and assembled into the lattice structure. Fig.4 shows a potential curve for explaining the displacement of the supplied atoms. "E" denotes the potential energy of the trap. If the potential E is bigger than the thermal energy kT of the atom, the probability that the atom escapes from the trap is low enough. Thus the atoms stop in the trap and form a part of lattice structure.

Since the substrate has a definite off-angle Θ from a (100) plane, the surface of the substrate forms a plurality of parallel steps. The planes parallel with a (100) plane are now called "terrace". The vertical parts are called "edges". The edges of the steps are the singular points for the crystal structure. The potential energy has the lowest at the singular points. Dislocations are defects of the periodic crystal structure. The dislocations have a low potential energy for atoms. Thus the dislocations can also trap atoms. "a" denotes the lattice constant. The terrace has a (100) plane. The height of the edge is "a", because the edge must be a unit of lattice structure. The length L of the terrace is L=a/Θ. L is also a distance between two neighboring edges. The edges are an assembly of parallel lines. The width of the terrace is denoted by "W". The length of the crystal is designated by "S". The area of the substrate is SW.

The flat parts (terraces) have a higher potential and the edges have a lower potential. Thus the terraces scarcely capture atoms because of the higher potential. Then most of the atoms will be captured either by dislocations or by the edges.

The atoms captured by the dislocations will be localized there and form a hillock, the Inventors surmise. Fig.2 and Fig.3 suggest that the hillocks are transcriptions of the dislocations. The hillocks should be made by the successive deposition of atoms on the dislocations. Namely, an abnormal growth on the dislocations makes hillocks.

By contrast, the atoms which are trapped at the edges of the steps form a part of an epitaxial film. When an atom is fixed at the edge, the terrace advances by a volume of an atom. If many atoms align at the edge, the terrace grows forward step by step. An advance of all the terraces by a distance L piles one atomic layer SW further on the substrate, because S/L terraces having a length L are arranged on the substrate and a progress L of the S/L terraces increases the volume of the crystal by LaWx S/L=SaW. Namely, the supply of atoms at the edges contributes to a normal growth.

When the inclination Θ of the surface to a (100) plane is small enough, the number of the terraces or the edges is also small. The atoms supplied on the surface have a poor chance of being captured by the step edges. Almost all of the falling atoms will be caught by the dislocations whose number is independent of the inclination Θ. The atoms will form big hillocks on the dislocations. Therefore a small Θ induces a high density of the hillocks.

As the inclination angle Θ from a (100) plane gains, the number N of the steps increases according to the equation $N = S\Theta/a$. Thus the increase of the number of the steps heightens the probability of catching atoms by the edges of the steps, and reduces the number of the atoms which are captured in the dislocations. The normal growth on the edges prevails in a big inclination Θ. The influential normal growth suppresses the abnormal growth, i.e. the origination of hillocks.

The mean distance of the paths along which the supplied atoms travel from the falling points to the nearest neighboring dislocations can be estimated by $D^{-\frac{1}{2}}$ which is an inverse of the root of the dislocation density D. By contrast, the mean distance of the paths along which the supplied atoms travel from the falling points to the nearest neighboring edges of the steps can be estimated by a/Θ which is a length of a terrace. Atoms replenished from the vapor phase will be captured by the nearer singular points (edges or dislocations). When a is small enough, the atoms are assembled at the dislocations. A plenty of hillocks are generated from the dislocations as seeds. When Θ is big, the atoms gather on the edges, which facilitates the normal growth of the film. Since few atoms are accumulated at the dislocations, few hillocks arise.

The problem which is dominant, the normal growth or the abnormal growth, depends on the relation between a/Θ and $D^{-\frac{1}{2}}$. These parameters include proportional constants. Then there must exist a critical off-angle $\Theta_o = KD^{\frac{1}{2}}$ which gives an equilibrium between the abnormal growth and the normal growth. When the inclination angle Θ is larger than Θ_o, the normal growth prevails and no hillocks appear. When Θ is smaller than Θ_o, hillocks originate from the dislocations on the substrate.

According to the measurement practiced by the Inventors, no hillocks occur at an angle Θ more than 0.04° for a dislocation density D = 1000cm^{-2}. No hillocks arise at an angle Θ more than 0.07° for a dislocation density D = 3000cm^{-2}. Similiarly no hillocks yield at an angle Θ higher than 0.2° in a dislocation density D = 25000cm^{-2}. The proportional constant K is calculated to be K = 1.26×10^{-3} deg · cm from these results. A fluctuation and an error sometimes accompany the measurement of the dislocation density. In this case, K = 1×10^{-3} deg · cm should be adopted instead of K = 1.26×10^{-3} deg · cm, because D cannot be determined by significant figures of three digits.

In the long run, the balance between the attraction force from the dislocations and the attraction force from the edges determines whether the supplied atoms are pulled by the dislocations or by the edges. "R" indicates the number of the atoms positioned on the terraces. "N" is the number of the atoms on the dislocations. "F" denotes the number of the atoms which are supplied to the substrate or the film in a unit time. "α" is the probability of the atoms for transferring from the terrace to the edges in a unit time. "β" is the probability of the atoms for being solidified at the edges. "γ" means the probability of the

atoms for moving from the terrace to the dislocations in a unit time. "δ" is the probability of the atoms of being solidified at the dislocations in a unit time. The following relations hold between the variables.

$$dR/dt = \alpha F - \beta R \qquad (1)$$

$$dN/dt = \gamma F - \delta N. \qquad (2)$$

F is the speed of the gas supply. Then F can be deemed a constant value. The probability α of the atoms to being captured by the edges which is in proportional to the number of the edges can be expressed by

$$\alpha = h\Theta. \qquad (3)$$

The probability β of the atoms for being solidified on the edges is contingent upon the temperature and the difference of potential between the edges and the terraces. But β is independent of the number of the edges. The probability γ of the atoms for being captured by the dislocations is in reverse proportion to the distance from the falling point to the nearest dislocation. Namely, the probability γ is in proportion to $D^{\frac{1}{2}}$. Then

$$\gamma = kD^{\frac{1}{2}}. \qquad (4)$$

δ is independent of the number of the dislocations, because it is the probability of the atoms for being solidified on the dislocations. δ is a function of the potential energy and the temperature. The differential equations are solved on the condition of keeping the supply F constant and on the initial condition of R = 0 and N = 0 at t = 0.

$$R = (\alpha F/\beta)\{1 - \exp(-\beta t)\} \qquad (5)$$

$$N = (\gamma F/\delta)\{1 - \exp(-\delta t)\} \qquad (6)$$

Since the atoms on the edges are solidified at the probability β in a unit time and the edges have R atoms, β R is the number of the atoms solidified on the edges in a unit time. The total number of the atoms solidified at the edges are given by integrating βR by time parameter t ($\int \beta$ Rdt). Similarly δ N is the number of the atoms solidified at the dislocations in a unit time. The total number of the atoms solidified at the dislocations is given by integrating δ N by t ($\int \delta$ Ndt). The change depending on time is only a transient change. Thus the total number of the atoms accumulated on the terraces is nearly equal to α tF. The atoms solidified on the dislocations are nearly γ tF.

The discovery of the Inventors is that the atoms growing on the dislocations form the hillocks. According to the opinion of the Inventors, the number of the atoms forming the hillocks is γtF. The solidification of αtF atoms at the edges of the steps corresponds to the normal growth of an epitaxial film. In order to make a thin film immune from the hillocks, αtF must be far bigger than γ tF. Namely, a should be still bigger than γ for the fabrication of non-hillock films. The condition is simply expressed by

$$h\Theta >> kD^{\frac{1}{2}} \qquad (7)$$

The condition of suppressing the occurrence of hillocks imposes a condition on Θ as $\Theta >> (k/h)D^{\frac{1}{2}}$. The prevention of hillocks demands the off-angle Θ to be bigger than

a value which is in proportion to the square root $D^{1/2}$ of the dislocation density D. This consideration coincides with the actual result. The proportional constant can be determined by the previous experiments. The condition is determined to be $\Theta \geq 1 \times 10^{-3} D^{1/2}$. Otherwise, $\Theta \geq (D/10^6)^{1/2}$.

This physical consideration corresponds to the discovery shown by Fig.2 and Fig.3 that the hillocks should be built by the atoms which are captured and solidified on the dislocations. The consideration can qualitatively explain the fact that the dislocation density of the substrate determines the minimum off-angle Θ_o preventing the hillocks from originating. Such a statistic consideration, however, cannot explain a non-linear and steep dependence on Θ of the hillock density, as shown in Fig.1, since it only gives a linear dependence on Θ of the hillock density

The assumption that the dislocations and steps compete with each other to attract the atoms supplied by the vapor phase sounds like a truth. But the assumption seems to have an unreasonable point quantitatively.

Now the lattice constant a is assumed to be 0.5 nm and the off-angle Θ from a (100) plane is also assumed to be 0.1°. Then the width of a terrace is 300 nm. By the way, the dislocation density is assumed to be 25000 cm^{-2}. In this case, the average distance between neighboring dislocations is about 60µm.

Even in such a big dislocation density, the average distance between the nearest neighboring dislocations is about 200 times as long as the length of the terraces An atom which has fallen at a spot in the middle of neighboring dislocations must climb up or down on about 100 steps of terraces till it reaches the nearest dislocations. The number of dislocations is too small in comparison with the number of the terraces.

Why is the atoms not attracted by the edges during rolling on the terraces and falling at the edges about 100 times? Why does the rapid fall of the hillock density occur at $\Theta = 0.09°$ in the case of D = 25000cm^{-2}? Why does the avalanche take place at 0.06° in the case of D= 3000 cm^{-2}? What does induce such a momentary descent at $\Theta = 0.03°$ for D=1000 cm^{-2}?

Fig.2 and Fig.3 indicate that a dislocation has a diameter of about 50µm. It the terraces have periodic lengths of a period of 0.3µm, one dislocation pervades more than 100 steps of the terraces A dislocation has an influence on the potential energy of a wide range of the terraces.

Then "βR" is now interpreted not as the atoms which are absorbed in the edges but as the height of the terraces. This interpretation is reasonable, because the height of the terraces is in proportion to the number of the atoms piling on the edges. Similarly the "δN" is interpreted as the height of the hillocks. δN has been the number of the atoms accumulated in the dislocations in the previous explanation. The height of the hillocks is obtained by dividing the number of the atoms adsorbed in the dislocations by the area of the dislocations. Since the

differential equations are linear about the variables R and N. the equations hold for the variables which are obtained by multiplying R and N by a multiplier.

The dislocations are far large odd-looking structures. The atoms which have once fallen on the dislocations may return back on the terraces. "ε" denotes the probability of the return of the atoms from the dislocations to the terraces. On the contrary, some atoms move from the terraces to the dislocations. "η" is the probability ot the movement of the atoms from the terraces to the dislocations. Then the motions of the atoms are explained by the following differential equations

$$dR/dt = \alpha F - \beta R + \epsilon N \qquad (8)$$
$$dN/dt = \gamma F - \delta N + \eta R \qquad (9).$$

The solutions include time-dependent parts and constant parts. The time-dependent parts rapidly diminish. The solutions soon attain equilibrium values

$$R = (\alpha \ \delta + \gamma \ \epsilon)F/\Delta \qquad (10)$$
$$N = (\beta \ \gamma + \eta \ \alpha)F/\Delta \qquad (11)$$
$$\Delta = \beta\delta - \epsilon\eta. \qquad (12)$$

Here Δ is positive, because the replacement rate ϵ from the dislocations to the terraces is far smaller than the solidification rate δ at the dislocations, and because the replacement rate η from the terraces to the dislocations is far smaller than the solidification rate β at the edges.

The height H_1 of the terraces is β Rt (In the strict sense of the word, the height is given by integrating βR by time t. But it attains an equilibrium value soon. Thus the integration is β Rt.)

$$H_1 = \beta (\alpha \ \delta + \gamma \ \epsilon)Ft/\Delta. \qquad (13)$$

In the similar meaning, the height H2 of the dislocations is δ Nt.

$$H_2 = \delta \ (\beta \ \gamma + \eta \ \alpha)Ft/\Delta. \qquad (14)$$

If the height of the dislocations is higher than the height of the terraces, the hillocks will grow indefinitely. On the contrary, if the height of the dislocations is lower than the height of the terraces, the hillocks will be fully covered with the terraces. The annihilation or generation of the hillocks depends on the tact whether H_1 is larger than H_2 or not. "Q" denotes the difference between H_1 and H_2.

$$Q = H_1 - H_2 = \{\beta \ \delta \ (\alpha - \gamma) + \beta \ \gamma \ \epsilon - \eta \ \alpha \ \delta\}Ft/\Delta. \qquad (15)$$

The sign of Q determines the structure of the film grown on the substrate. Conspicuously different structures are produced by plus Q and minus Q. If Q is positive, the dislocations will be fully covered with an assembly of terraces, since the terraces grow more rapidly than the hillocks. Namely, a positive Q kills the influence of the dislocations and ensures to grow a smooth film without hillocks. Since Q is a positive value, the sign (positive or negative) of Q depends only on the sign of the value bracketed. If the values in the bracket are positive, the dislocations disappear and no hillocks grow. Since ε or η is trivial, what determines the sign of Q is the difference

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$(\alpha - \gamma)$. Since $\alpha = h\Theta$ and $\gamma = kD^{\frac{1}{2}}$, $(\alpha - \gamma)$ is positive, when $\Theta > (k/h)D^{\frac{1}{2}}$. Here the constants k and h are different from the previous constants k and h.

On the contrary, if Q is negative, the abnormal structure on the dislocations grows more rapidly than the terraces. The abnormal structures project on the film and enlarge everlastingly. These abnormal structures on the dislocations are the hillocks. Thus when $\Theta < (k/h)D^{\frac{1}{2}}$, the hillocks appear on the film.

This consideration is capable of explaining the narrow transition area in which the hillock density falls rapidly in Fig.1 as well as the relation between Θ and D. In Fig.1, $\Theta = 0$ gives the equation H = D for any value of D. Some inclination angle Θ rapidly reduces the hillock density H to H = 0. Such a quick transition of the hillock density H is induced by a sudden change of the sign of Q which is the difference between the terrace growing speed and the abnormal structure growing speed.

For example, the hillock density H is about 10000 cm^{-2} at $\Theta = 0.06°$ in the case of D = 25000cm^{-2}. H reduces to about 1000cm^{-2} at $\Theta = 0.07°$. Furthermore, H decreases to 40 cm^{-2} at $\Theta = 0.10°$. These rapid fall of H is induced by an abrupt change of the sign of Q at about $\Theta = 0.07°$. From $\Theta = 0.07°$, the growth speed of the terraces slightly surpasses the growth speed on the dislocations. Even though the difference of the speeds is small, the terraces can cover the abnormal growth on the dislocations. Then the hillocks are concealed by the terraces. Therefore, the sudden change of the hillock density can be consistently explained by the change of the sign of Q.

Θ must become bigger than (k/h)D$^{\frac{1}{2}}$ for annihilating the hillocks. 0.20° for D=25000 cm^{-2} at which H falls to zero is a value larger than the critical parameter (k/h)D$^{\frac{1}{2}}$ for D=25000 cm^{-2}. Similarly 0.07° for 3000 cm^{-2} and 0.04° for D=1000 cm^{-2} are bigger than the values (k/h)D$^{\frac{1}{2}}$ for D = 3000 cm^{-2} and D = 1000 cm^{-2}, respectively.

Claims

1. An epitaxy for growing compound semiconductors comprising the steps of;
   preparing an InP substrate having a defect density D (cm^{-2}) and an inclination angle Θ (degree) from a (100) plane which satisfies an inequality $\Theta \geq 1 \times 10^{-3} D^{\frac{1}{2}}$; and
   growing one or more than one compound semiconductor films on the InP substrate by a vapor phase epitaxial growth method.

2. An epitaxy for growing compound semiconductors comprising the steps of;
   preparing an InP substrate having a defect density D and an inclination angle Θ from a (100) plane which satisfies an inequality $\Theta \geq 1.26 \times 10^{-3} D^{\frac{1}{2}}$; and
   growing one or more than one compound sem-

iconductor films on the InP substrate by a vapor phase epitaxial growth method.

3. An epitaxy as claimed in claim 1 or 2, wherein a material of the compound semiconductor films is InP, InGaAsP or InGaAs.

4. An epitaxy as claimed in claim 3, wherein the vapor phase epitaxial method is the MOCVD (Metal-Organic Chemical Vapor Deposition) method.

5. An epitaxy as claimed in claim 3, wherein the vapor phase epitaxial method is the MBE (Molecular Beam Epitaxy) method.

6. An epitaxy as claimed in claim 3, wherein the vapor phase epitaxial method is the chloride CVD (Chloride Chemical Vapor Deposition) method.

7. An epitaxy as claimed in claim 3, wherein the vapor phase epitaxial method is the halogen transport CVD (Halide Chemical Vapor Deposition) method.

8. An InP wafer having a defect density D and an off-angle Θ from a (100) plane which satisfies an inequality $\Theta \geq 1 \times 10^{-3} D^{\frac{1}{2}}$.

9. An InP wafer having a defect density D and an off-angle Θ from a (100) plane which satisfies an inequality $\Theta \geq 1.26 \times 10^{-3} D^{\frac{1}{2}}$.

FIG.1

(cm⁻²)

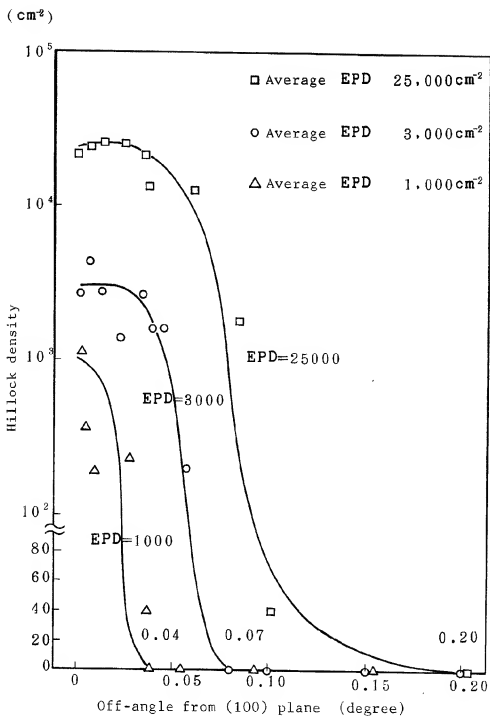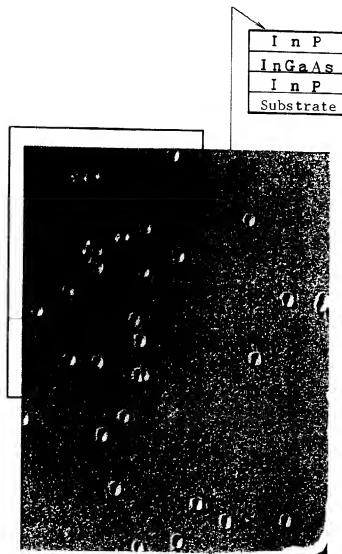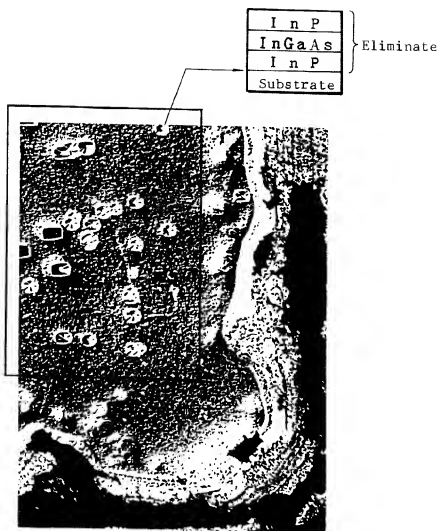Off-angle from (100) plane (degree)

FIG.2

Hillocks appearing on the top layer
of films grown on InP substrate by OMVPE

Substrate = Fe-doped InP

FIG.3
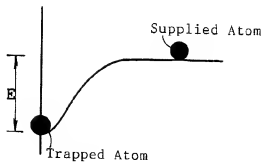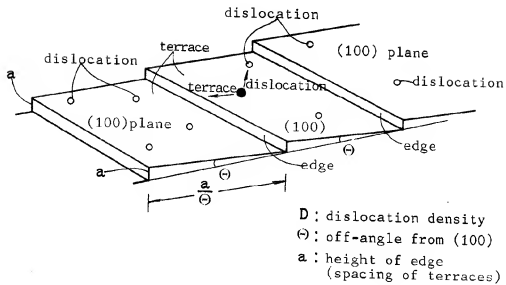
Etch pits on substrate etched by Hüber etching

InP
InGaAs
InP
Substrate

} Eliminate

Substrate = Fe-doped InP

FIG.4

E

Supplied Atom

Trapped Atom

FIG.5

dislocation

terrace

dislocation

(100) plane

(100)plane

terrace dislocation

dislocation

(100)

dislocation

edge

edge

a

a

$\frac{a}{(\cdot)}$

(·)

D : dislocation density
(·) : off-angle from (100)
a : height of edge
    (spacing of terraces)

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(54) Epitaxy for growing compound semiconductors and an InP substrate for epitaxial growth

(57) Hillocks arise on the films, when compound semiconductor films are grown on an InP wafer having a surface near a (100) orientation. Off-angle wafers have been adopted for a substrate in order to suppress the occurrence of hillocks. The off-angle Θ from a (100) plane is not a sole factor for ruling the generation of hillocks. There is a concealed parameter which determines the generation of hillocks. What induces hillocks on the growing film is the defects on the substrate itself. No hillocks originate on a part of an InP wafer without dislocations. The role of the off-angle Θ of the substrate is preventing the influence of the dislocations from transmitting to the films. A smaller density D of the defects on the substrate allows a smaller off-angle Θ for suppressing the hillocks from arising. A bigger density D of the defects demands a larger off-angle for the substrate so as to forbid the hillocks from originating. An inequality $Θ \gtrsim 1 \times 10^{-3}D^{1/2}$ is the condition for annihilating hillocks. More precise condition is $Θ \gtrsim 1.26 \times 10^{-3}D^{1/2}$.

FIG. 5

dislocation
dislocation
terrace
(100) plane
dislocation
o dislocation
dislocation
terrace
(100) plane
(100)
edge
edge
a Θ
a Θ
a

D : dislocation density
Θ : off-angle from (100)
a : height of edge
(spacing of terraces)

European Patent Office

EUROPEAN SEARCH REPORT

Application Number

EP 95 30 6232

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
A,D	PATENT ABSTRACTS OF JAPAN vol. 013, no. 195 (E-754), 10 May 1989 & JP-A-01 015914 (NEC CORP), 19 January 1989, * abstract * ---	1-9	C30B25/18
A,D	PATENT ABSTRACTS OF JAPAN vol. 013, no. 220 (E-762), 23 May 1989 & JP-A-01 032686 (NEC CORP), 2 February 1989, * abstract * -----	1-9	
			TECHNICAL FIELDS SEARCHED (Int.Cl.6) C30B

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	22 April 1996	Flink, E

CATEGORY OF CITED DOCUMENTS

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